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keynote summary

Mechanisms Underlying ACL Injury-Prevention Training: The Brain-Behavior Relationship

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In an attempt to elucidate the biomechanical and neuromuscular risk factors associated with anterior cruciate ligament (ACL) injuries in female athletes, numerous authors have examined sex differences in the performance of athletic tasks. Such investigators have consistently reported that lower extremity mechanics differ between males and females. For example, females exhibit decreased knee and hip flexion and increased quadriceps muscle activation, knee valgus angles, and valgus moments when compared with males.[1–8] Taken together, this biomechanical and neuromuscular profile is thought to place greater loads on the ACL.

Although the reasons underlying the sex differences in the performance of athletic maneuvers are not fully understood, evidence suggests that differences in proximal control may play a contributory role. Our group[9] has reported that females favor use of the knee extensors over the hip extensors to attenuate impact forces during a drop-landing task (ie, higher knee-extensor moments relative to hip-extensor moments and greater energy absorbed at the knee in relation to the hip). In comparison, male athletes were shown to attenuate impact forces through more equal use of the knee and hip extensors.[9] Theoretically, if the hip extensors do not contribute to control of the body's center of mass during landing, females may compensate through an overreliance on their quadriceps (ie, knee stiffening), by absorbing impact in the frontal plane (ie, greater knee valgus angles or moments), or both.[10]

Insufficient training has been hypothesized to underlie the observed "at-risk behavior" demonstrated by female athletes. To address this issue, several injury-prevention programs have been developed. Although the types of exercises in and the duration of each program differ, they generally include elements of endurance, flexibility, strengthening, and proprioceptive training. A recently published meta-analysis[11] demonstrated a significant effect of injury-prevention training on ACL injury incidence in female athletes.

The success of ACL injury-prevention programs is encouraging, but little is known about the behavioral changes that accompany these programs. Our group (Pollard et al[13]) recently completed a pretest-posttest biomechanical evaluation of the Prevent Injury and Enhance Performance (PEP) program developed by the Santa Monica Orthopaedic and Sports Medicine group.[12] We (Pollard et al[13]) demonstrated that increased use of the hip musculature appears to underlie the protective effect afforded by injury-prevention training. More specifically, girls, adolescent girls, and women who underwent a 10-week ACL injury-prevention training program decreased their knee-extensor moments and increased their hip-extensor moments during landing. Furthermore, greater energy was absorbed at the hip (relative to the knee) posttraining. As a result of these findings, we have proposed that injury-prevention training may decrease mechanical loading at the knee through increased use of the hip musculature.

Despite the evidence suggesting that training can alter biomechanical and neuromuscular risk factors that may contribute to ACL injury, it remains to be seen whether changes in behavior after participation in an injury-prevention program result from peripheral adaptations (muscle strengthening), central adaptations (motor reprogramming), or both. The fact that movement behavior has been reported to be independent of strength[14] suggests that posttraining changes may reflect improvements in motor control.

Recent advances in neuroscience research suggest that alterations in the human brain occur in response to intensive motor-skill learning.[15] This "experience-dependent plasticity" refers to changes that occur in the brain (morphologic and molecular) as a result of experience.[16] Experience-dependent plasticity underlies the acquisition of skilled behavior in healthy humans. Additionally, increasing evidence indicates that plastic changes in the primary motor cortex play an important role in skill acquisition.[17]

In the last decade, transcranial magnetic stimulation (TMS) has been used to explore cortical plasticity during motor learning in the intact human cortex. Transcranial magnetic stimulation is a noninvasive, painless method for stimulating the brain. Experience-dependent neuroplasticity can be demonstrated in human participants by examining the posttraining responsiveness (excitability) of corticomotor circuitry to TMS. Changes in corticomotor excitability occur in response to behavioral and environmental manipulations such as skill training.[18] In contrast to skill acquisition, non–skill training, such as muscle-specific strength training, has been reported to elicit no or only minor changes in excitability.[19] On the basis of these findings, motor-skill acquisition rather than movement repetition seems to be a prerequisite for driving cortical plasticity related to motor experience.

Our group has undertaken a series of pilot studies to investigate whether there is evidence of neuroplasticity after ACL injury-prevention training. Given that increased use of the hip extensors appears to underlie the protective effect afforded by injury-prevention training, our focus has been on evaluating corticomotor excitability of the gluteus maximus. As part of this work, we compared the effects of a 10-week lower extremity strength-training program (20 sessions) with a 10-week skill-acquisition training program (20 sessions) in which volunteers were instructed in proper landing mechanics. Although this pilot study was performed on only 4 females ($n = 2$ per group), the following observations were made: (1) skill-acquisition training was superior to strength training in eliciting landing strategies thought to be "ACL protective," (2) changes in behavior observed immediately after skill-acquisition training were retained at 6-month follow-up, suggesting that motor learning had occurred, and (3) increased use of the hip extensors immediately after and 6 months after skill-acquisition training was associated with *decreased* corticomotor excitability of the gluteus maximus.

These observations provide support for the premise that neuroplastic changes in the brain are associated with skill acquisition and may underlie the changes in behavior associated with injury-prevention training. Of note, we observed plasticity in the form of *diminished* excitability. A decrease in corticomotor excitability is consistent with the reduced corticomotor excitability during postural tasks reported by researchers[20,21] focusing on supraspinal adaptations in response to balance training. A decrease in corticomotor excitability suggests that subcortical neural sites, such as the striatal or cerebellar circuits (or both), have become more relevant in the generation of muscular output.[22] Furthermore, the fact that long-term training induced "semipermanent" changes in gluteus maximus excitability may reflect structural plasticity, such as long-lasting strengthening of synaptic efficacy.

The results of this pilot study suggest that neuroplastic changes in the brain may underlie the changes in behavior associated with injury-prevention training that is focused on skill acquisition. It is possible that the observed decrease in corticomotor excitability may represent a reallocation of control toward subcortical motor regions after skill training rather than reflecting an increase in strength. Our preliminary findings are encouraging because they are consistent with the results of studies showing decreases in cortical activity (functional magnetic resonance imaging) and corticomotor excitability (TMS) in response to long-term execution of skilled movements.[12,21]

Summary

In young female athletes, ACL tears are a common and debilitating injury. Given the detrimental effect of ACL injury, considerable effort has been directed toward the development of injury-prevention strategies. Although ACL injury-prevention training is being advocated in various sport settings, programs are being implemented without a thorough understanding of why they work and how they are best delivered. Ongoing research suggests that the protective effect afforded by injury-prevention training may be the result of skill acquisition associated with central adaptations (ie, motor learning). Future research efforts should be directed at identifying optimal training methods that elicit long-term changes in behavior that are considered ACL protective.

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